

# CTA simulations with CORSIKA/sim\_telarray

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**Abstract.** While current atmospheric Cherenkov installations consist of only a few telescopes each, future installations will be far more complex. Monte Carlo simulations have become an essential tool for the design and optimisation of such installations. The CORSIKA air-shower simulation code and the `sim_telarray` code for simulation of arrays of Cherenkov telescopes have been used to simulate several candidate configurations of the future Cherenkov Telescope Array (CTA) in detail. Together with other detailed and simplified simulations the resulting data provide the basis for the ongoing optimisation of CTA over a wide energy range. In this paper, the simulation methods are outlined and preliminary results on a number of configurations are presented. It is demonstrated that the initial goals of the CTA project can be achieved with available technology, at least in the medium and high energy range (about 100 GeV to 100 TeV).

**Keywords:** Monte Carlo simulation; Air showers; Imaging atmospheric Cherenkov technique; Gamma-ray astronomy

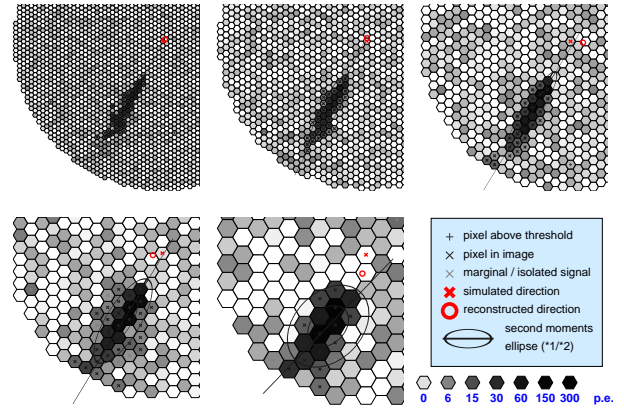
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## INTRODUCTION

The Cherenkov Telescope Array (CTA) project design study [1] is under way to design and optimise the next generation of stereoscopic Imaging Atmospheric Cherenkov Telescope (IACT) arrays. CTA aims to achieve an order of magnitude improvement in point-source sensitivity over current instruments and a wider energy coverage in order to study astrophysical processes of more sources in more detail.

While extrapolation from current generation instruments may be a first guide to what is needed to achieve the CTA goals, only detailed simulations can give definite answers. Physical processes in air showers may ultimately limit the gamma-hadron separation power of the instruments, as well as their angular and energy resolution. Depending on area coverage and instrumental capabilities, any affordable solution will typically not reach such ultimate limits. The approach in this paper is the evaluation of realistic – or conservative – performance parameters by detailed simulations of air showers and the potential instruments, followed by analysis methods well tested on current instruments.

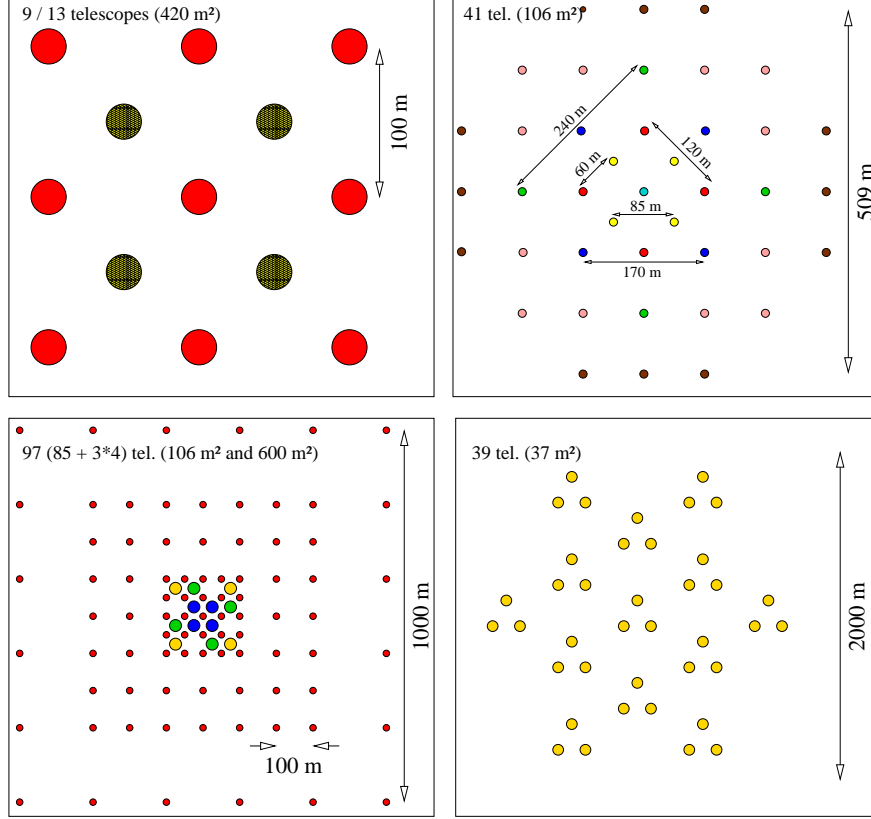
The air-shower simulation is based on the CORSIKA [2] code with its choice of different interaction models. With the IACT option of CORSIKA we can simulate the Cherenkov light hitting arbitrary arrays of telescopes, each defined separately by its position and a fiducial radius. Since the CORSIKA stage requires the largest amount of CPU time, each shower is re-used at different random displacements. Due to the excellent gamma-hadron separation of all the configurations envisaged, a huge number of hadron showers has to be simulated in order to estimate the remaining backgrounds – in most



**FIGURE 1.** Different pixel sizes can have an impact on the image obtained from the same shower (here  $0.07^\circ$  to  $0.28^\circ$  pixels on a 23 m telescope, only part of f.o.v. shown). CORSIKA output can be piped directly into multiple telescope simulations running in parallel, allowing for efficient simulation of different configurations. (See Figure 3 for results.)

cases billions of events.

In a second processing stage, the atmospheric extinction and the details of the detector response are simulated by the `sim_telarray` program [3]. This program is very flexible and different detectors with different read-out, different triggering schemes, or just different reflectors are treated by the same code, by just specifying different configuration files. Simulations include optical ray-tracing, night-sky background, all relevant electronic pulse shapes, switching behaviour of comparators or discriminators, as well as many other details. Telescope configurations are tested for random night-sky trigger rates before being used for shower simulations.



**FIGURE 2.** Selection of different array configurations simulated for altitudes of 1800 to 2000 m. See text for more details.

For efficiency reasons, the CORSIKA output data is usually piped into the telescope simulation, without intermediate on-disk storage. By placing a utility program termed `multipipe_corsika` into this pipe, the CORSIKA data can be piped into multiple telescope simulations at the same time, e.g. for different pixel sizes (see Figure 1), different offset angles etc.

## A VARIETY OF CANDIDATE CONFIGURATIONS

Since the performance is a complex function of array layout (which may consist of multiple types of telescopes), and of a variety of telescope parameters, detailed simulations can be performed only for a limited – and therefore rather complementary – subset of layout and telescope parameters. These candidate configurations (see Figure 2) include:

- A 9-telescope array aiming at low energies (420 m<sup>2</sup> mirror area each, with 0.1° pixels covering a 5° field-of-view (f.o.v.). This configuration was simulated at different altitudes (2000 m, 3500 m, and 5000 m a.s.l.). The 2000 m simulations were car-

ried out with a variety of pixel sizes (from 0.07° up to 0.28°, see Figure 1). It was also cross-checked with an different telescope simulation code [4].

- An array of 41 H.E.S.S.-I type telescopes (106 m<sup>2</sup>), to see how gamma-hadron rejection can be improved by better coverage with current-generation instruments. It also allows to test arrays of 4, 5, 9, or 16 telescopes with different inter-telescope separations by selecting subset of the 41 telescopes in the analysis.
- An array consisting of telescopes of two different sizes (600 m<sup>2</sup> and 106 m<sup>2</sup> mirror area, 5° and 7° f.o.v.) aiming at a rather wide energy coverage. For the large telescopes, three sets of four telescopes each, with different separations, were included in the simulation – usually selecting only one set of four large plus the 85 small telescopes in the analysis. All telescopes were assumed to have a 50% higher quantum efficiency than H.E.S.S.
- Different arrays of rather small (37 m<sup>2</sup>) telescopes with large separations and wide-f.o.v. cameras (up to 8° with 0.3° pixels), aiming at high energies.

Simulations include gammas, protons, and electrons as primaries – nuclei, being generally easy to distinguish from gammas, were not considered. All simulations were carried out at the Max Planck Institute in Heidelberg, except for the 3500 m 9-telescope configuration which was processed at SLAC.

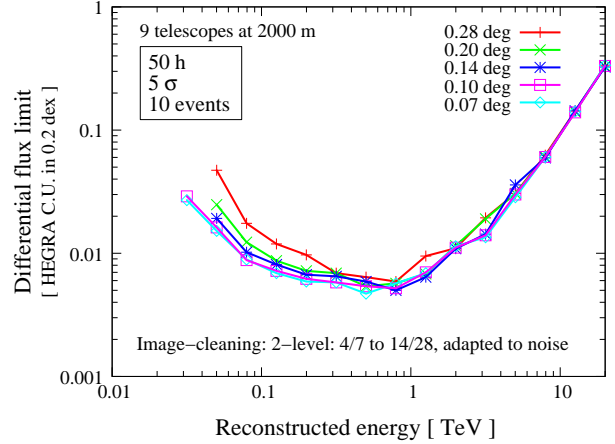
## ANALYSIS

The analysis of simulation data is based on methods similar to the H.E.S.S. Hillas-parameter based standard analysis, with some extensions like using the height of shower maximum and how well the lateral distribution conforms with expectations for gamma showers. Image shape cuts include the mean reduced scaled width and length [6]. Since, after geometrical shower reconstruction, the image in each telescope can be used for an energy estimate, the consistency of the individual estimates for the same event is used as another cut. Showers where the expected accuracy of the final (weighted mean) energy estimate is poor for the given energy, e.g. showers outside the array, are also discarded. At the lowest energies, a few tens of GeV, the image shape cuts typically have little gamma-hadron discrimination power. The most important parameter in this energy range turned out to be the height of shower maximum. Selection cuts were manually optimised as simple functions of reconstructed energy or telescope multiplicity (e.g. of the form  $a + b \log E$ , with additional lower and upper bounds). Further improvements by more sophisticated shower reconstruction and advanced cut optimisations may be feasible. In that sense, the following performance results are very conservative.

The set of cuts from the H.E.S.S. standard analysis was also used on H.E.S.S.-I simulations as well as corresponding four-telescope subsets of the 41-telescope array, with corresponding sensitivities matching the actual H.E.S.S. sensitivity [6].

## PERFORMANCE RESULTS

The performance of the tested CTA candidate configurations was evaluated for point sources, usually taking advantage of the angular resolution improving with increasing number of telescopes with usable images. Since the rejection of hadronic background improves with increasing energy, most selection cuts have to be rather strict at low energies and get looser towards higher energies. Both proton and electron background was included, with the electron flux extrapolated  $\propto E^{-3.3}$  beyond available measurements. In contrast to naïve expectations, electrons never dominated the background at the lowest energies, due to the energy-dependent hadron rejection ef-



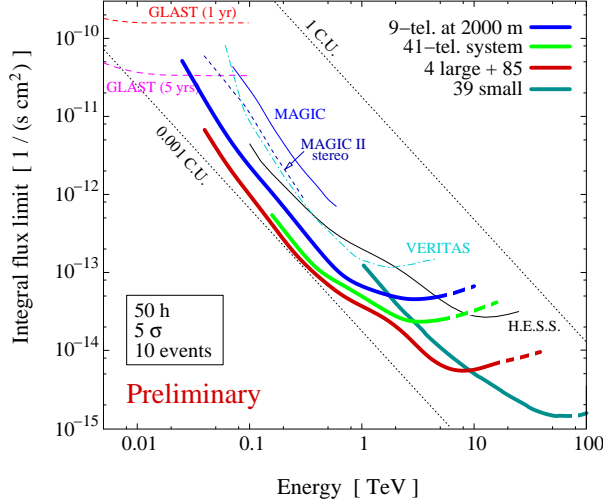
**FIGURE 3.** Differential sensitivity limit (with 5 sigma, 10 events in each energy bin) in HEGRA Crab units [5] for the 9-telescope array at 2000 m altitude, at a zenith angle of 20°. Each curve is for one of the pixel sizes in Figure 1. Since the larger pixels will see more night-sky background noise, it is important to adapt image cleaning thresholds to this noise. Only at very low energies any improvement could be achieved by small pixels.

iciency. In the evaluation of flux limits, the Li&Ma formula was used to find the minimum number of gammas to achieve a 5-sigma significance. In addition, a minimum of 10 gammas was required. At very low energies, another limitation had to be taken into account: the systematics in the subtraction of remaining background, here assumed at a level of 1% being equivalent to a 1-sigma fluctuation.

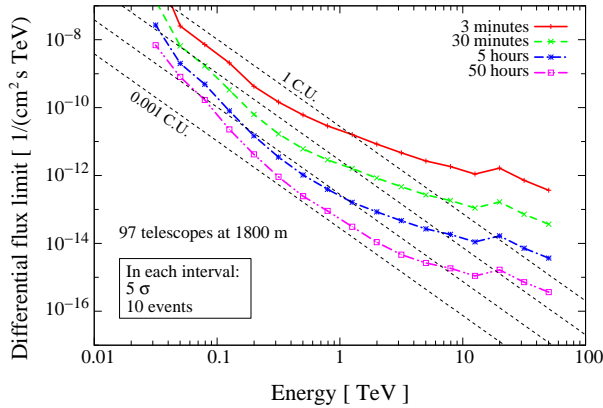
It turns out that with the arrays of nine 420 m<sup>2</sup> telescopes the energy threshold can in fact be reduced to some 20 GeV. Rather strict selection cuts are needed at the lowest energies to achieve sufficient gamma-hadron separation to avoid running into the limitation by background systematics.

The 41-telescope array of 106 m<sup>2</sup> telescopes would not substantially improve the energy threshold compared to the four-telescope H.E.S.S. phase I array. Thanks to the much better sampling of the showers it would however improve gamma-hadron separation, angular resolution, and effective area compared to H.E.S.S.-I, resulting in a sensitivity improvement much faster than the naïve  $1/\sqrt{N}$  expectation ( $N$  being the number of telescopes).

The 97-telescope array (of which usually 85 small plus 4 large telescopes were used in the analysis) combines low energy threshold with much improved gamma-hadron rejection. In fact, the presence of the smaller telescopes helps to improve the gamma-hadron rejection even in the energy domain normally only accessible to the large telescopes – by rejecting hadron showers where a sub-shower may look like a low-energy gamma-ray



**FIGURE 4.** Point source sensitivity limits  $F(>E)$  of the four arrays from Figure 2 at  $20^\circ$  zenith angle, compared with current instruments [6, 7, 8, 9]. One C.U. (Crab unit) in this case is  $F_{\text{Cu}}(>E) = 1.78 \cdot 10^{-7} (E/\text{TeV})^{-1.57} \text{ photons}/(\text{m}^2 \text{ s})$  [5].



**FIGURE 5.** Differential sensitivity limit (with 5 sigma, 10 events in each energy bin of 0.2 dex) for the 97-tel. configuration, with different exposure times, from 3 minutes to 50 hours. A 1 hour exposure would be enough for a high-quality spectrum of a 0.1 Crab source over two orders of magnitude in energy. 50 hours would be needed for the spectrum of a milli-Crab source. One C.U. (Crab unit) is assumed here as  $dF_{\text{Cu}}/dE = 2.79 \cdot 10^{-7} (E/\text{TeV})^{-2.57} \text{ photons}/(\text{m}^2 \text{ s TeV})$  [5].

shower. At intermediate energies, this configuration fully meets initial goals for CTA (“milli-Crab sensitivity”).

At the highest energies envisaged for CTA, even the square kilometre area of the 97-telescope configuration may not be sufficient to detect enough events. It could be supplemented with additional small telescopes instrumented with much coarser pixels (up to  $0.3^\circ$ ) and operated at larger inter-telescope separations. This is demonstrated by the assumed 39-telescope array.

## CONCLUSIONS AND OUTLOOK

The combination of the CORSIKA and sim\_telarray programs is very well suited for simulations of large telescope arrays, even with hundreds of telescopes. It is also very flexible and can be adapted to arbitrary array configurations and telescope setups just by means of run-time configuration. The subsequent analysis with its Hillas-parameter based shower reconstruction results in rather conservative performance estimates. Arrays consisting of multiple telescope types are easily handled in all stages. First simulations included a range of different test configurations, with emphasis on different energy ranges, and demonstrated that the CTA sensitivity goal can be achieved [4] – at least for energies above 50 to 100 GeV. Future simulations will include more realistic CTA configurations (within budget constraints) as well as some corner cases needed to improve the CTA design optimisation scheme.

## ACKNOWLEDGMENTS

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